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14. ABSTRACT Experimental research has been conducted in order to establish the new quantum key distribution system for secure and undecipherable quantum communications. The system has been based on optical single-photon transmitters and superconducting single-photon detector receivers. The photon transmitters were based on heavily attenuated femtosecond optical pulses, generated by a high-repetition-rate laser. Novel superconducting devices were designed and developed for efficient and ultrafast counting of visible-light and near-infrared (telecommunication wavelength) photons. The devices were fabricated as nanostructured superconducting NbN serpentine lines with the active area of 100 micrometers squared and operated at 4.2 K inside a cryostat. The detector experimental quantum efficiency reached above 10% for visible-light and up to 8% for near-infrared photons. The dark counts were 0.1 per second. The real-time photon counting rate was above 2 GHz and jitter was 18 ps. In terms of the photon-counting performance, our detectors are significantly better than any competing avalanche photodiodes and photomultipliers.					
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Summary:

Experimental research has been conducted in order to establish the new quantum key distribution system for secure and undecipherable quantum communications. The system has been based on optical single-photon transmitters and superconducting single-photon detector receivers. The photon transmitters were based on heavily attenuated femtosecond optical pulses, generated by a high-repetition-rate laser. Novel superconducting devices were designed and developed for efficient and ultrafast counting of visible-light and near-infrared (telecommunication wavelength) photons. The photon counters were operated in the quantum detection mode, based on photon-induced hotspot formation and subsequent appearance of a transient resistive barrier across an ultrathin and submicron-width superconducting stripe. The devices were fabricated as nanostructured NbN interdigitated serpentine lines with the nominal active area $10 \times 10 \mu\text{m}^2$ and operated at cryogenic (liquid helium) temperatures inside a cryostat. The detector experimental quantum efficiency in the photon-counting mode reached above 10% in the visible range of radiation and up to 8% at the 1.3- to 1.55- μm range. The dark counts were below 0.1 per second. The measured real-time counting rate was above 2 GHz and jitter was below 18 ps, both limited by our readout electronics. In terms of the photon-counting efficiency, speed, and jitter, our NbN superconducting single-photon detectors are significantly better than any competing semiconductor avalanche photodiodes and photomultipliers.

Objectives:

The objective of this research effort was to establish the new quantum key distribution (QKD) communication system, based on optical single-photon transmitters (Quantum Alice) and receivers (Quantum Bob). The program brought together UR and IF AFRL researchers to achieve the development of both fiber-optic and free-space high-speed QED prototype systems. The objective of this project were achieved through realization of 4 separate tasks, aimed to:

- develop superconducting single-photon counters, integrated into the “Quantum Bob” receivers for Gb/s digital clock rates for secure quantum communication;
- establish jitter-free fast-laser transmitter (Quantum Alice) with single-picosecond pulses carrying on average one photon per pulse and characterized by the repetition rate ranging from 100 MHz to 3 GHz;
- perform simulations and computer characterization of the quantum communication channel in the QKD system, including impact of privacy amplification and authentication, and signal propagation in lossy (e.g., Earth atmosphere) media (This task was led by IF AFRL.);
- establish a comprehensive subpicosecond and nanoscale characterization facility at the University of Rochester for testing and characterization of quantum information transmitter/receiver devices and quantum computation systems. Train and educate a new generation of scientists in the area of quantum information electronics and photonics.

Realization of Objectives:

All objectives set in the research goal of this grant have been reached. In particular, we have developed novel superconducting single-photon detectors (SSPDs) for ultrafast counting of the visible-light and near-infrared photons for secure quantum communications and quantum cryptography. Our devices consist of nanostructured NbN interdigitated serpentine lines, have the nominal active area $10 \times 10 \mu\text{m}^2$ and operate at 4.2 K, well below the NbN superconducting transition temperature. The SSPDs operate in the quantum detection mode, based on photon-induced hotspot formation and subsequent appearance of a transient resistive barrier across an ultrathin and submicron-width superconducting stripe. Our best devices achieve experimental quantum efficiency (QE) from >10% for 405-nm radiation to ~5% for 1550-nm photons, real-time counting rate of >2 GHz, jitter <18 ps, and dark counts <0.1 per second. In terms of the photon-counting speed and jitter, our SSPDs significantly outperform semiconductor avalanche photodiodes and photomultipliers.

We have also established our Ultrafast Quantum Phenomena Laboratory for testing quantum information transmitter/receiver (Alice/Bob) devices. We performed extensive characterization of our photodetectors both in terms of QE and the speed of response. Our measurements were performed in the simulated Alice-Bob scenario in the photon wavelengths ranging from visible light to near infrared (telecommunication).

Accomplishments/New Finding:

Ultrafast digital data processing and "unlimited" bandwidth communication, including quantum computing and quantum information, are the most crucial elements for the Air Force future missions and warfare.

- (1) We experimentally demonstrated unique advantages of our detectors for ultrafast quantum key distribution and communications. The experimental QE of our NbN SSPDs in the photon-counting mode reached above 10% in the visible range of radiation and up to 8% at the 1.3- to 1.55- μm near-infrared range. The dark counts were below 0.1 per second and the noise-equivalent power (NEP) was $2 \times 10^{-17} \text{ W/Hz}^{1/2}$ at 1.3 μm —the record low value for any near-infrared photon counters. See publications: [1], [4], and [9].
- (2) We have studied time-resolved dynamics of the resistive-state formation in 10-nm-thick, 130-nm-wide NbN superconducting stripes exposed to single photons and observed a $65(\pm 5)$ -ps time delay in the switching onset. The time-delay phenomenon has been explained within the framework of a model based on photon-induced generation of a hotspot in the superconducting stripe. The measured time delays in both the single-photon and two-photon detection regimes agree well with theoretical predictions of the resistive-state dynamics in quasi-one-dimensional superconducting stripes. Fluctuations of the time-delay values have been identified as the source of jitter, measured in our SSPDs. See publications: [2], [5], [10], and [11].
- (3) We have tested our SSPDs specially designed for near-infrared quantum communications and quantum key distribution (Quantum Bob). The measurements were performed using a Pritel fiber-mode-locked laser (Quantum Alice), which generated a train of 1.6-ps-wide optical pulses with the telecommunication wavelength of 1.55 μm . The Pritel laser variable repetition rate ranged from 1 GHz to 3 GHz. Real-time counting of 1.55 μm photons was performed. The actual measured counting rate was up to 2 GHz and was limited by our readout electronics (the intrinsic response time is below 30 ps). The SSPD jitter was below 18 ps, the lowest value reported for any photon detectors. See publications: [3], [7], [8], and [13].
- (4) Our SSPDs have been implemented in a VLSI CMOS integrated circuit testing system, based on the detection of time-resolved, near-infrared photon emission from switching transistors. The system was commercialized by NPTest Inc., the leader in advanced tools for VLSI microchips debugging in the semiconducting industry. The patent protection for the SSPD was filed in the US Patent Office. We also received the 2003 *R&D Magazine* Award for one of the 100 most innovative products developed worldwide in 2003. See publications: [6], [14], and [15].

- (5) In direct collaboration with the Moscow State Pedagogical University in Russia, we have developed advanced technology for fabrication of nanostructured SSPDs. With the help of AFRL/SNDD and their focused ion beam (FIB) tool, we have begun to define the SSPD stripe width to the scale of the film thickness (4 nm). The initial sample fabrication, demonstrated the exquisite process control, however, the sample was not superconducting. We attempted to refine the dimensional and fabrication constraints to obtain operational devices, unfortunately, the FIB process poisoned the NbN thin film and resulted in nonsuperconducting meander stripes.
See publications: [12] and [16].

- (6) We established Ultrafast Quantum Phenomena Laboratory at the University of Rochester. The Ultrafast Lab is dedicated to basic and applied research on ultrafast phenomena in solids and on novel materials, devices, and testing technologies for optoelectronic quantum information systems. This is an interdisciplinary effort, which combines condensed matter physics and quantum electrodynamics with optics, nanoelectronics, and cryogenics.
See website: <http://www.ece.rochester.edu/projects/ufqp/index.html>

Table below summarizes our in the SSPD development supported by this grant, by directly comparing the SSPD performance with other advanced, semiconductor single-photon devices and with the W transition edge sensor (bolometer) developed at NIST, Boulder, CO. The comparison has been done for the telecommunication wavelength 1.3 μm . We see that in terms overall performance our SSPDs significantly outperform any currently available competing technologies for single photon counting.

PERFORMANCE OF DIFFERENT SINGLE-PHOTON DETECTORS OPERATING AT $\lambda = 1.3 \mu\text{m}$

Detector Model	Counting rate (Hz)	QE (%)	Jitter (ps)	Dark Counts (s ⁻¹)	NEP (W/Hz ^{1/2})
InGaAs PFD5W1KS APD (Fujitsu)	5×10^6	>20	>200	6×10^3	3×10^{-17}
R5509-43 PMT (Hamamatsu)	9×10^6	1	150	1.6×10^4	$\sim 10^{-16}$
Si APD SPCM-AQR- 16 (EG&G)	5×10^6	0.01	350	25	$\sim 10^{-16}$
W bolometer- 0.1 K (NIST)	2×10^4	>90	N/A	$<10^{-4}$	$<10^{-19}$
SSPD - 4.2 K	2×10^9	8	<18	<0.1	2×10^{-17}

Personnel Supported:

Professor Roman Sobolewski, PI – part-time summer
Dr. Aleksandr Verevkin, Scientist – part-time
Dr. Wojciech Slys, Visiting Scientist – part-time
Mr. Aaron Pearlman, graduate student
Mr. Jin Zhang, graduate student
Ms. Jennifer Kitaygorodskaya, graduate student
Mr. Daozhi Wang, graduate student

Completed Ph. D. Thesis

Jin Zhang (Ph. D. MSC, April 2004) Thesis: "Ultrafast NbN Superconducting Single-Photon Detectors for Noninvasive CMOS Circuit Testing."

Books and Book Chapters

1. "Optical Sensors," (Chapter) R. Sobolewski and D. P. Butler, in: Handbook of Superconducting Materials, ed. by D. Cardwell and D. Ginley, pp. 1855-1866, Institute of Physics Publishing Ltd., Bristol, UK (2002).

Refereed Publications:

16. "Nanostructured superconducting single-photon detectors," G. Gol'tsman, A. Korneev, V. Izbenko, K. Smirnov, P. Kouminov, B. Voronov, N. Kaurova, A. Verevkin, J. Zhang, A. Pearlman, W. Slys, and R. Sobolewski, Nucl. Meth. Phys. Res. A, **520**, pp. 527-529 (2004).
15. "Non-invasive CMOS circuit testing with NbN superconducting single-photon detectors," J. Zhang, N. Boiadjeva, G. Chulkova, H. Deslandes, G. N. Gol'tsman, A. Korneev, P. Kouminov, M. Leibowitz, W. Lo, R. Malinsky, O. Okunev, A. Pearlman, W. Slys, A. Verevkin, K. Wilsher, C. Tsao, and R. Sobolewski, Elect. Lett., **39**, No. 14, pp. 1086-1088 (2003).
14. "GHz counting rate NbN single-photon detector for IR diagnostics of VLSI CMOS circuits," A. Korneev, A. Lipatov, O. Okunev, G. Chulkova, K. Smirnov, G. Gol'tsman, J. Zhang, W. Slys, A. Verevkin, and R. Sobolewski, Microelectron. Eng., **69**, Nos. 2-4, pp. 274-278 (2003).
13. "Ultrafast Superconducting Single-Photon Optical Detectors and Their Applications," (Invited) R. Sobolewski, A. Verevkin, G. N. Gol'tsman, A. Lipatov, and K. Wilsher, IEEE Trans. Appl. Supercon. **13**, No. 2, pp. 1151-1157 (2003).
12. "Fabrication of Nanostructured Superconducting Single-Photon Detectors," G. N. Gol'tsman, K. Smirnov, P. Kouminov, B. Voronov, N. Kaurova, V. Drakinsky J. Zhang, A. Verevkin, and R. Sobolewski, IEEE Trans. Appl. Supercon. **13**, No. 2, pp. 192-195 (2003).
11. "Response Time Characterization of NbN Superconducting Single-Photon Detectors," J. Zhang, W. Slys, A. Verevkin, O. Okunev, G. Chulkova, A. Korneev, A. Lipatov, G. N. Gol'tsman, and R. Sobolewski, IEEE Trans. Appl. Supercon. **13**, No. 2, pp. 180-183 (2003).

10. "Time Delay of the Resistive State Formation in Superconducting NbN Stripes Illuminated by Single Optical Photons", J. Zhang, W. Slys, A. Verevkin, R. Sobolewski, O. Okunev, and G. N. Gol'tsman, Phys. Rev. B **67**, No.13, pp. 132508-1-4 (2003).
9. "Ultrafast Superconducting Single-Photon Optical Detectors," (Plenary Lecture) R. Sobolewski, J. Zhang, W. Slys, A. Pearlman, A. Verevkin, A. Lipatov, O. Okunev, G. Chulkova, A. Korneev, K. Smirnov, P. Kouminov, B. Voronov, N. Kaurova, V. Drakinsky, and G. N. Gol'tsman, in: Advanced Optical Devices, Technologies, and Medical Applications, ed. by J. Spigulis, J. Teteris, M. Ozolinsh, and A. Lasis, Proc. SPIE **5123**, pp. 1-11 (2003).
8. "Ultrafast Superconducting Single-Photon Detectors for Infrared Wavelength Quantum Communications" (Invited Lecture), A. Verevkin, A. Pearlman, W. Slys, J. Zhang, R. Sobolewski, G. Chulkova, O. Okunev, P. Kouminov, V. Drakinskij, K. Smirnov, N. Kaurova, B. Voronov, G. N. Gol'tsman, and M. Currie, in: Quantum Information and Communication, ed. by E. Donkor, A. R. Pirich, and H. E. Brandt, Proc. SPIE **5105**, pp. 160-169 (2003).
7. "Superconducting Single-Photon Detectors for GHz-Rate Free-Space Quantum Communications," (Invited) A. Verevkin, J. Zhang, W. Slys, R. Sobolewski, A. Lipatov, O. Okunev, G. Chulkova, A. Korneev, and G. N. Gol'tsman in: Free-Space Laser Communication and Laser Imaging II, ed. by J. C. Ricklin and D. G. Voelz, Proc. SPIE vol. 4821, pp. 447-454, (2002).
6. "An Ultrafast NbN Hot-Electron Single-Photon Detector for Electronic Applications", A. Lipatov, O. Okunev, K. Smirnov, G. Chulkova, A. Korneev, P. Kouminov, G. N. Gol'tsman, J. Zhang, W. Slys, A. Verevkin, and R. Sobolewski, Supercon. Sc. & Tech. **15**, pp. 1689-1692 (2002).
5. "Spectral Sensitivity and Temporal Resolution of NbN Superconducting Single-Photon Detectors," A. Verevkin, J. Zhang, W. Slys, R. Sobolewski, A. Lipatov, O. Okunev, G. Chulkova, A. Korneev, K. Smirnov, G. N. Gol'tsman, and A. Semenov, in Proc. of Thirteen Int. Symposium on Space Terahertz Technology, Harvard Univ. Press, pp. 105-111 (2002).
4. "Detection Efficiency of Large-Active-Area NbN Single-Photon Superconducting Detectors in the Ultraviolet to Near-Infrared Range", A. Verevkin, J. Zhang, R. Sobolewski, A. Lipatov, O. Okunev, G. Chulkova, A. Korneev, K. Smirnov, and G. N. Gol'tsman, and A. Semenov, Appl. Phys. Lett. **80**, No. 20, pp. 2644-2646 (2002).
3. "Ultrafast Superconducting Single-Photon Optical Detectors and Their Applications," (Invited), A. Verevkin, A. Lipatov, G. N. Gol'tsman, and R. Sobolewski, in OPTO-Canada: SPIE Regional Meeting on Optoelectronic, Photonics, and Imaging, Proc. SPIE vol. TD01, pp. 39-40 (2002).
2. "Time-resolved Characterization of NbN Superconducting Single-Photon Optical Detectors," J. Zhang, A. Verevkin, W. Slys, G. Chulkova, A. Korneev, A. Lipatov, O. Okunev, G. N. Gol'tsman, and R. Sobolewski, in OPTO-Canada: SPIE Regional Meeting on Optoelectronic, Photonics, and Imaging, Proc. SPIE vol. TD01, pp. 33-35 (2002).
1. "Spectral Sensitivity of the NbN Single-Photon Superconducting Detector" (Invited), R. Sobolewski, Y. Xu, X. Zheng, C. Williams, J. Zheng, A. Verevkin, G. Chulkova, A. Korneev, A. Lipatov, O. Okunev, K. Smirnov, and G. N. Gol'tsman, IEICE Trans. Electron. **E85-C**, No. 3, pp. 797-802 (2002).

Interactions/Transitions:

- (a) Participation/presentations at meetings, conferences, seminars, etc.
25. "Single-Photon and Ultrafast Optical Detectors," presented at the Laboratory for Laser Energetics (Science and Technology Seminar Series), University of Rochester, Rochester, NY, January 2004.
 24. "Ultrafast Superconducting Single-Photon Optical Detectors," presented at the Photonics Center, Boston University, Boston, MA, January 2004.
 23. "Ultrafast Superconducting Single-Photon Optical Detectors and Their Applications," presented at the Institute of Photonics and Quantum Electronics, Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland, December 2003.
 22. "Ultrafast Superconducting Single-Photon Optical Detectors and Their Applications," presented at the Group of Applied Physics, University of Geneva, Geneva, Switzerland, December 2003.
 21. "Ultrafast Superconducting Single-Photon Optical Detectors and Their Applications," presented at the MIT Lincoln Laboratory, Lexington MA, November 2003.
 20. "Superconducting Optical Detectors and Their Applications," R Sobolewski, presented at the European Applied Superconductivity Conference, Sorrento, Italy, September 2003.
 19. R. Sobolewski participated in the AFOSR Research Review Meeting, New York, NY, May 2003, and presented a lecture entitled: "Quantum Key Distribution Using Single Polarized Photons."
 18. A. Verevkin participated in SPIE AeroSense 2003, Quantum Information and Communication Conference, Orlando, FL, May 2003, and presented INVITED lecture entitled: "Ultrafast Superconducting Single-Photon Detectors for Infrared Wavelength Quantum Communications."
 17. A. Verevkin participated in NIST Workshop on Novel Radiation Detectors, Gaithersburg MD, April 2003, and presented INVITED lecture entitled: "GHz-Rate Superconducting Photon Counting Detectors."
 16. R. Sobolewski visited the Institute for Thin Film and Interfaces Seminar, Research Center Juelich, Juelich Germany, March 2003, and presented a colloquium entitled: "Single-photon and ultrafast optical detectors."
 15. R. Sobolewski visited the Department of Physics, Humboldt University Berlin, Berlin, Germany, January 2003, and presented a colloquium entitled: "Ultrafast Superconducting Single-Photon Optical Detectors and Their Applications."
 14. R. Sobolewski presented at the Laboratory for Laser Energetics, University of Rochester, Rochester, NY, December 2002, the talk entitled: "Ultrafast Superconducting Single-Photon Optical Detectors and Their Applications."
 13. R. Sobolewski visited the NSF Center for Quantum Device Technology at Clarkson University, Postdam NY, November 2002, and presented a colloquium entitled: "Ultrafast Superconducting Single-Photon Optical Detectors and Their Applications."

12. R. Sobolewski participated in SPIE International Conference on Advanced Optical Materials and Devices, Riga, Latvia, August 2002, and presented PLENARY lecture entitled: "Ultrafast Superconducting Single-Photon Optical Detectors."
11. R. Sobolewski, J. Zheng, and A. Verevkin participated in the Applied Superconductivity Conference (ASC'2002), Houston TX, August 2002 and presented INVITED talk entitled: "Ultrafast Superconducting Single-Photon Optical Detectors and Their Applications," and poster entitled: "Response Time Characterization of NbN Superconducting Single-Photon Detectors."
10. A. Verevkin participated in SPIE Annual Meeting Conference on Free-Space Laser Communication and Laser Imaging, Seattle, WA, July 2002, and presented INVITED talk entitled: "Superconducting Single-Photon Detectors for GHz-Rate Free-Space Quantum Communications."
9. R. Sobolewski, J. Zheng, A. Verevkin, and A. Pearlman participated in the SPIE Regional Meeting – Ultrafast Lasers, OPTO-Canada 2002, Ottawa, Canada, May 2002 and presented INVITED talk entitled: "Ultrafast Superconducting Single-Photon Optical Detectors and Their Applications," and a poster entitled: "Time-resolved Characterization of NbN Superconducting Single-Photon Optical Detectors."
8. R. Sobolewski visited the University of Naples "Federico II," Naples, Italy, March 2002, and presented a colloquium entitled: "Ultrafast Quantum Phenomena in Nonequilibrium Superconductors."
7. R. Sobolewski participated in the Knowledge Foundation's International Conference on Applications of Superconductors in Microelectronics, Communication, and Computing, Boston, MA, November 2001, and presented INVITED talk entitled: "Picosecond Superconducting Single-Photon Optical Detectors and Their Applications."
6. R. Sobolewski participated in the Symposium on Materials Research (SOMR2001), Rochester, NY, November 2001, and presented INVITED talk entitled: "Ultrafast Superconducting Optoelectronics."
5. R. Sobolewski visited the Naval Research Laboratory – Space Sciences Division, Washington, DC, February 2002, and presented a seminar entitled: "Superconducting Single-Photon Optical Detectors and Their Applications."
4. R. Sobolewski participated in the AFOSR Research Review Meeting, Palo Alto, CA, October 2001, and presented talk entitled: "Quantum Key Distribution Using Single Polarized Photons."
3. R. Sobolewski participated in the Superconducting Electronics Workshop, Lake Arrowhead, CA, October 2001, and presented INVITED talk entitled: "Superconducting Optoelectronics."
2. R. Sobolewski participated in the MITRE Workshop on Quantum Cryptographic Applications, McLean, VA, July 2001, and presented INVITED talk entitled: "Ultrafast Superconducting Single-Photon Detectors."
1. R. Sobolewski participated in the 8th International Superconductive Electronics Conference (ISEC'97), Osaka, Japan, June 2001, and presented INVITED talk entitled: "Ultrafast Optoelectronic Interface for Digital Superconducting Electronics."

- (b) Consultative and advisory functions to other laboratories and agencies, especially Air Force and other DoD laboratories.
- 4. R. Sobolewski attended the ONR Superconducting Electronics Program Review, at Melbourne, FL, February 2003, and presented a seminar entitled: "Magneto-optical output from RSFQ circuits."
- 3. R. Sobolewski collaborated extensively with Dr. D. Nicholson at the AFRL/IFGC Optical Communications Group, Rome NY and with Dr. Glen David Via at the AFRL/SNDD, Dayton OH, 2002.
- 2. R. Sobolewski visited Dr. Kent S. Wood at the Naval Research Laboratory Space Sciences Division, Washington, DC, February 2002, to discuss the joint research program. He also presented a seminar entitled: "Superconducting Single-Photon Optical Detectors and Their Applications."
- 1. R. Sobolewski visited Dr. D. Nicholson at the AFRL/IFGC Optical Communications Group, Rome NY, Nov. 2001 to discuss our joint research program on quantum communications.

(c) Transitions.

The company NPTest from San Jose, CA, the largest producer of the digital circuit testing equipment provides continued funding for developing single-photon NbN photodetectors for their new generation of OptiCA[®] systems. The Rochester detectors are implemented in commercial OptiCA[®] testers.

New discoveries, inventions, or patent applications:

- 1. "Superconducting Single Photon Detector," R. Sobolewski, G. N. Gol'tsman, A. Semenov, O. Okunev, K. Wilsher, and S. Kasapi – US Patent pending.

Honors/Awards:

- 5. R&D100 Award for the development of a Superconducting Single-Photon Detector, *R&D Magazine* 2003.
- 4. R. Sobolewski was selected a Member of the Electronics Program Sub-Committee, Applied Superconductivity Conference (ASC'2002), Houston TX, 2002.
- 3. R. Sobolewski was promoted to the rank of Professor with Unlimited Tenure of Electrical and Computer Engineering at the University of Rochester, 2002.
- 2. R. Sobolewski was promoted to the rank of Professor of Electrical and Computer Engineering at the University of Rochester, 2001.
- 1. R. Sobolewski was selected a Member of the International Advisory Committee of the Vilnius International Symposium on Ultrafast Phenomena in Semiconductors, Vilnius, Lithuania, 2001.